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ORIGINAL ARTICLE

Ultrasonic welding of dissimilar metals, AA6061 and Ti6Al4V

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Abstract Ultrasonic welding of Ti6Al4V sheet and A6061 aluminum alloy sheet was conducted. The influence of ultrasonic welding parameters on the mechanical properties, the interface microstructure, the micro-hardness and the composition diffusion of the welded joint was investigated. It was shown to be possible to join Ti6Al4V sheet and A6061 aluminum alloy sheet through ultrasonic welding. After ultrasonic welding, the hardness of both the matrices increased, and there appeared to be some amount of diffusion across the welding interface. Various welding pressures and welding times were used and the strength of the welded joint was at its optimal value with a welding pressure of 0.4 MPa and a welding time of 170 ms.

Keywords Ultrasonic welding · Dissimilar metals · Welding pressure · Welding time

1 Introduction

The welding of dissimilar metals is a process of joining two or more metal materials which can be undertaken at certain conditions. It is difficult to join dissimilar materials because of their differences in chemical composition, physical and chemical properties. The hard and brittle intermetallic compounds of Al alloy and Ti alloy are easy to form at a welding interface using a conventional welding process, such as electric arc welding or gas metal arc welding [1–3]. Currently, the main joining methods for Al/Ti dissimilar alloys are vacuum brazing [4], friction welding [5, 6], diffusion welding [7, 8], explosive welding [9], and laser welding [10, 11] and so on.

Here, a solid-phase joining method of ultrasonic welding process is developed to join titanium alloy to aluminum alloy. The ultrasonic welding process is used to weld thin layers of metal at low temperature, low pressure, and low energy consumption [12]. As a cold and low pressure process, it could be widely applied to welding dissimilar metal, such as joining of aluminum and ceramic [13], aluminum alloy and stainless steel [14].

Aluminum alloys have low density and low cost and titanium alloys could offer an advantage in comparison to conventional materials due to their high strength, stiffness and corrosion resistance. Hybrid structures of aluminum and titanium alloy materials have been widely used, which with light-weight construction techniques, and commercially available and qualified materials, can achieve the appropriate balance between performance and cost. It is well known, for example, that the cooling fin used in aeroplane cabins is made up of the welding of an aluminum (3003) blade and a titanium pipe, and the honeycomb structure of the plane's wings is often a composite structure in which a titanium skin is joined to an aluminum honeycomb. The advantage of joining dissimilar metal materials is the low weight, high strength-to-weight ratio, high fatigue resistance, and higher anti-vibration limit and stability that can be achieved [15]. Hybrid structures, and components made of aluminum and titanium materials have been used in aerospace applications, especially aircraft [16]. The wings of the experimental NASA YF-12 fighter were made up of a honeycomb composite plate of Al/Ti. The airplane will feature titanium plates and a composite

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Table 1 Composition of aluminum alloy 6061

Alloying element	Cu	Si	Fe	Mn	Mg	Zn	Cr	Ti	Al
Composition (%)	0.15–0.4	0.4–0.8	0.7	0.15	0.8–1.2	0.25	0.04–0.35	0.15	Balance

structure of aluminum ribs in the aircraft seat rails and in areas particularly subject to corrosion in order to improve the corrosion resistance, reduce the weight and reduce the manufacturing costs [17].

This paper presents a study of the ultrasonic welding of 6061 aluminum alloy sheet-titanium alloy sheet (Ti6Al4V), including the analysis of the mechanical properties, observations of the microstructure, and the analysis of the composition diffusion and the nanoidentation hardness. AA 6061 and Ti6Al4V were chosen for the study as they were deemed the two materials most likely to be used in spacecraft construction.

2 Materials and experimental methodology

2.1 Materials

The compositions of the aluminum alloy (AA6061) sheets and the titanium alloy (Ti6Al4V) sheets used in the current study are listed in Tables 1 and 2.

Alloy 6061 is a representative 6000 series aluminum alloy, containing magnesium and silicon as its major alloying elements. It has moderate strength, high corrosion resistance and exhibits good weldability. 6061 is widely used for the construction of various industrial structures that require medium strength and high corrosion resistance, such as in trucks, tower buildings, ships, trolleys, railway vehicles, furniture [18]. It is one of the most common alloys of aluminum in general purpose use.

Ti6Al4V is an alpha–beta alloy and offers a combination of high structural stability, high toughness, plasticity, corrosion resistance, and good deformation properties at high temperature. It can be worked by hot pressing, quenching, and aging to strengthen the alloy. By doing so, its strength is increased by 50–100% more than annealing after heat treatment. It can be used long-term at high temperatures of 400–500°C and maintain its high strength. Its thermal stability is similar to that of alpha titanium alloy. These properties make Ti6Al4V the most popular of the titanium alloys, being used for a range of applications in the aerospace, marine, power generation, and offshore industries [18].

2.2 Experimental methodology

The materials studied are aluminum alloy 6061 and Ti6Al4V in the form of sheets with 0.3 mm thickness, cut into 200 mm×10 mm rectangles. 6061 aluminum alloy and Ti6Al4V titanium alloy are chemically active, easily oxidized in the air, and produce dense oxide films (Al_2O_3, TiO_2) to affect the welding process. Ultrasonic welding is a combination of both surface and volume softening effects. The surface softening effects can break up the surface oxide layer and other contaminants, but the broken pieces of oxides and contaminants will remain in the welding interface. It is necessary to remove the oxide film before welding in order to get a good welding effect. The surface oxide film of 6061 aluminum alloy is mechanically broken because the material is relatively soft in contrast to the Ti6Al4V in the ultrasonic welding process, which does not affect the performance of the weld. The Ti6Al4V sheet oxide film surfaces were sanded to obtain a welding surface with metallic luster before the experiment. Then, under ultrasonic welding, the dissimilar metal A6061 and Ti6Al4V were joined. A schematic diagram of the metal ultrasonic welding machine is shown in Fig. 1; it is rated at 3.2 kW and frequency f=20 kHz, with a 125 mm beam tool-steel sonotrode, ending with a 15×15-mm square tip with a sand grinding surface.

During the welding process, the sonotrode oscillates transversely to the direction of welding (see Fig. 1). Contact pressure that applied on the sonotrode interacts with the oscillating shear forces causes dynamic internal stresses at the interface between the two mating surfaces. The major adjustment process parameters are static pressure and welding time. In case of welding pressure, the welding machine can generate three pressures—0.3, 0.4, and 0.5 MPa. Welding times were chosen as 90, 110, 140, 170, and 200 ms. Table 3 lists all input factors and their levels. The experiment was conducted using a full factorial design and the number of experimental conditions was 15 with ten replicates for each test condition. A total of 150 samples were prepared for the peel test to determine optimum welding parameters. Then, the welding specimens were prepared using the optimum welding parameters for the micro-hardness test.

Table 2 Composition of Ti6Al4V

Alloying element	Al	V	Fe	O	Si	C	N	H	Other	Ti
Composition (%)	5.5–6.8	3.5–4.5	0.3	0.2	0.15	0.1	0.05	0.01	0.5	Balance

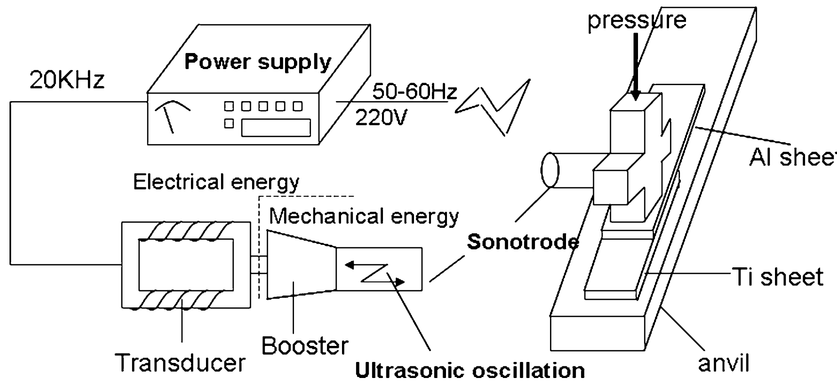


Fig. 1 Basic principles of metal ultrasonic welding

3 Results and discussion

3.1 Mechanical properties analysis

The tensile/shear test method was selected to determine weld quality, which was realized using a tensile testing machine (see Fig. 2) according to the Chinese national standard GB/T 2651–1989 [19]. When applied to 6061 and Ti6Al4V specimens, failure tended to propagate around the welding point. This indicated that the welding achieved an effective bond, and showed the strength of the weld over the strength of the aluminum alloy matrix. Meanwhile, there was a greater stress concentration adjacent to the weld.

Figure 3 shows the highest resistance to peeling at different welding times and welding pressures. From Fig. 3, under different static pressures, with the increase in welding time, the peeling force tended to increase linearly first then remained basically unchanged. However, with the continued increase in the welding time, the peeling force decreased. The reason was that even though welds were produced there may be some regions where no atomic bonds were present, either because the joint strength was too low with a short welding time or because of the presence of residual oxide at the weld interface. With an extension of the welding time, the joint strength rapidly increased. However, the strength of the welding decreased when the welding time was over a certain value. For peel test experiments, the reasons for this reduction in strength were twofold. On the one hand, as the heat of the specimen intensified, there was plastic zone expansion which weakened the cross-section. And on the other hand, when the welding time was too long, this caused fatigue cracks to the surface and internally, which reduced the welding strength. The optimal welding time depend on the properties, thickness, and other process parameters of the welded material. From an analysis of the testing data the conclusion was reached that the optimal welding time was 170 ms with the different static pressures of 0.3, 0.4, and 0.5 MPa.

During welding, a contact pressure was applied to the sonotrode, and ultrasonic vibration energy was effectively transferred to the specimen through the sonotrode. From Fig. 3, under a welding static pressure of 0.4 MPa, the shearing force is larger than that under 0.3 and 0.5 MPa. It is impossible to bond for over low pressure cannot produce surface deformation. The reason is that ultrasonic energy cannot transfer to the specimen meaning that an insufficient amount of frictional work is produced in the specimen. Almost all the ultrasonic energy is lost in surface slippage between the sonotrode and the specimen. With the increase in static pressure, the transfer conditions of vibrational energy are improved, thus leading to a temperature rise in the welding interface, a decrease in the material deformation resistance and plastic flow gradually increased, thus the result that the joint strength increases. However, the strength of the weld would decrease due to vibration energy not being effectively applied when the welding static pressure is over a certain degree. The excessive contact pressure makes friction too large, causing relative friction motion in the specimen, or even reduces the effective amplitude. The bonding area is reduced and weakens the contact interface surface for the material being crushed. The analysis of testing data leads to the conclusion that the optimal welding pressure is 0.4 MPa during ultrasonic welding.

Table 3 Factors and levels for experimental design

Factors	Factor name	Levels
P	Welding pressure (MPa)	0.3, 0.4, 0.5
T	Welding time (s)	90, 110, 140, 170, 200

3.2 Micro-hardness analysis

Micro-hardness was measured by HXS-1000A Vickers hardness tester with a load of 100 gf and a holding time of 15 s. The spacing of the adjacent indentation was set at 25 μm and the six hardness values of sample were measured. Figure 4 shows the increasing in the hardness in the vicinity of the weld interface which means that after ultrasonic

Fig. 2 Tensile/shear test setup for the specimens

welding the hardness of the matrices increased, compared with that of the original metal material, especially in the region around the weld interface in the Ti6Al4V side. Because plastic deformation causes dislocation movement, and dislocation stress fields interact with each other, the existence of one dislocation will hinder the movement of the others.

3.3 EDS analysis

Figure 5 shows SEM images and the results of line analysis near the joint interfaces by EDS under different welding time. As seen in Fig. 5, there appears to be some amount of diffusion across the interface. It is obvious that as the welding time increases, the width of diffusion layer also increases, which explains how ultrasonic welding can achieve atomic bonding between metals. When the welding time is 90 ms, the width of the diffusion layer is about 1.4 μm; when the welding time is 140 ms, the width of the diffusion layer is about 2.1 μm; when the welding time is 200 ms, the width of the diffusion layer is about 3.8 μm. One reason is as the welding time increases, the atoms diffusion time increases. Another reason is the atomic diffusion coefficient would exponential increase with the temperature increases [20], while the weld interface temperature significantly increases with welding time increases.

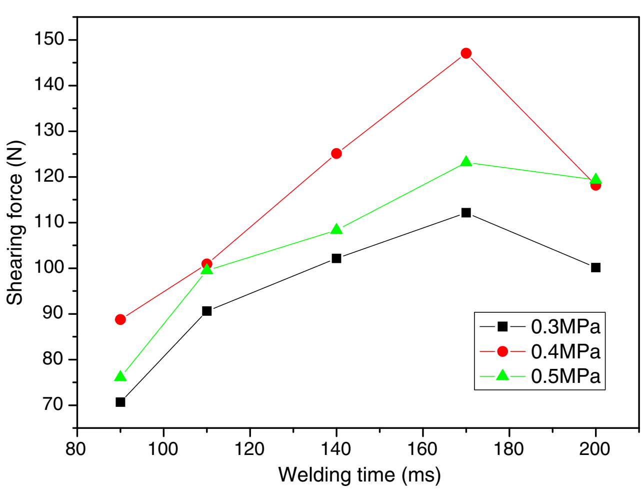


Fig. 3 The relationship between welding time and peeling force under different welding pressure

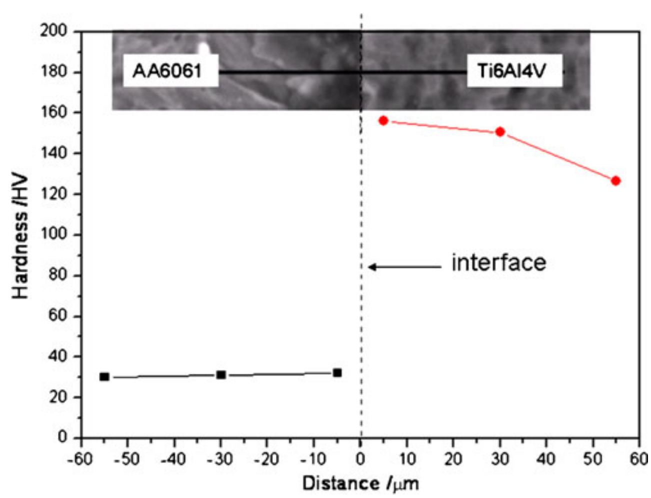
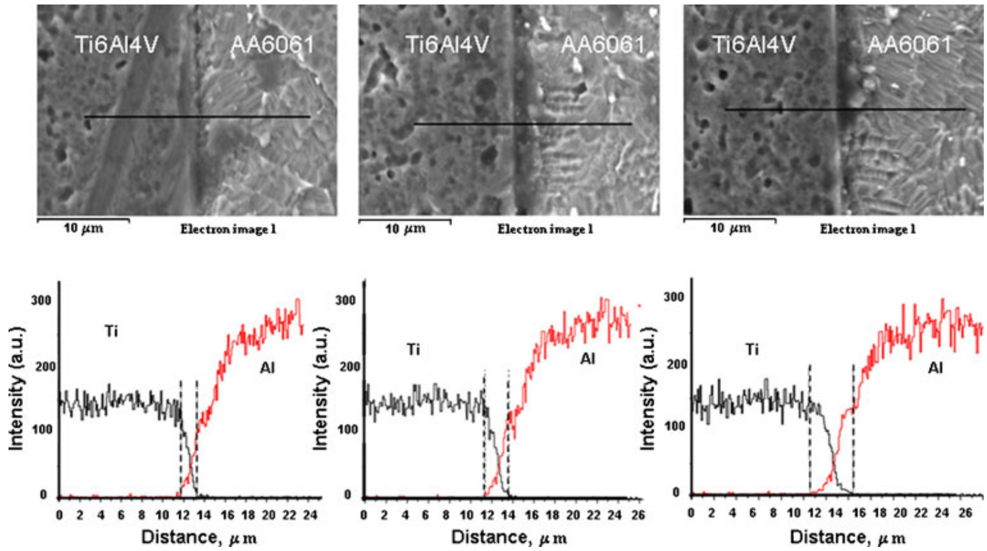


Fig. 4 Micro-hardness distribution along the cross-section of the bond interface



a) 90ms b) 140ms c) 200ms

Fig. 5 Cross-sectional SEM images and result of line analysis near the joint interfaces by EDS under different welding time

4 Conclusion

AA6061 and Ti6Al4V were ultrasonically welded and the effect of welding parameters on the mechanical properties and the interface microstructure of welded joint were investigated. The analyses showed that:

(1) Ti6Al4V sheet and AA6061 aluminum alloy sheet were bonded effectively using ultrasonic welding.
(2) A welding pressure of 0.4 MPa and a welding time of 170 ms were found to be the optimal process parameters, in terms of producing the strongest joint.
(3) After ultrasonic welding the hardness of all matrices increased, compared with that of the original metal material, especially in the region around the weld interface.
(4) There appeared to be some diffusion across the welding interface and the width of the diffusion zone increases with the welding time increases.

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